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Thermal and optical analysis of a passive heat recovery and storage system for greenhouse skin

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Abstract

The thermal performance of a greenhouse can be greatly affected by the thermal and optical properties of its envelope system. In this study, a novel skin for greenhouse consisting of ethene-co-tetrafluoroethene (ETFE) membrane and Phase Change Material (PCM) RT28 has been developed and has also been experimentally investigated. The optical behaviour of the developed ETFE-Phase Change Material module sample is measured using a spectrometer and a pyranometer, respectively. The results show that at liquid state, the module has higher transmittance than that of at solid state. In addition, the light transmittance is related to the PCM's temperature. In the thermal aspect, the ETFE-Phase Change Material module presents different characterisation under various irradiances. Comparative analysis is also conducted for the ETFE-Phase Change Material, ETFE-water and ETFE alone. The ETFE-Phase Change Material system shows a benefit of the thermal management than that of other systems.

Keywords: ETFE; Phase Change Materials; Optical performance; Thermal performance; Greenhouse.

1. Introduction

Nowadays, due to the rapid population growth and ever greater product demand, greenhouse industry has become a fast-growing segment of agriculture and horticulture throughout the world. Greenhouses protect cultivation using

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techniques providing partially or fully controlled micro-climate for plant growth, therefore, it improves the yield and quality of plant in different climatic regions, and the growing seasons of crops in variety are extended.

Conventional greenhouses are generally characterised as the infrastructures with transparent thin glass sheets or plastic coverings. Therefore, it would be difficult to maintain the required inner environment, such as lighting, temperature, humidity, etc. The envelopes of conventional greenhouses are highly transparent to the incident irradiation and are able to block the longwave infrared radiation emitted from the interior objects such as soil and plants, therefore, without sufficient ventilation and cooling, this accumulated heat within the greenhouse would cause overheating in a typical sunny day. On the other hand, because of poor thermal insulating, conventional greenhouses usually require heating systems to compensate the excessive heat in cold weather to maintain a suitable temperature for plant growth. Space heating of traditional greenhouses is mainly driven by the consumption of fossil fuels [1], which can lead to increase of carbon footprint as well as financial burden on the greenhouse owners. In recent years, great efforts have been expended in seeking alternatives to improve the thermal performance and energy efficiency of greenhouses. Among these, Phase Change Material (PCM) energy storage technique represents a highly efficient solution to moderate the greenhouse's temperature increase and reduce the heating/cooling load.

PCMs are referred to as the substances that can store and release a considerable amount of heat when undergoing isothermal or near-isothermal phase transition process. They can be classified into three groups: organic, inorganic and eutectic. Compared with sensible storage materials such as water and rock, PCMs can accumulate 5~14 times more energy per unit volume with relatively lower temperature variation [2]. In addition, PCMs have a wide range of phase-transition temperatures that can be fitted to a spectrum of heating and cooling needs. In building section, PCMs can be encapsulated into the opaque components such as walls, or filled into the transparent components like double-glazing panel. In the past decade, there have been an increasing amount of studies carried out regarding the thermal and optical performance of glazed units incorporated with translucent PCMs [3]. Weinlader et al. [4] investigated the performance of a double glazed units with three PCMs integrated: a RT25 paraffin, S27 based on $CaCl_2 \cdot 6H_2O$ and L30 based on $LiNO_3 \cdot 3H_2O$. The glazing panel with PCM showed approximately 30% less heat loss in south oriented façade compared to a double-glazed unit without PCM, and a 50% reduction in solar heat gain. The obtained *U*-value is between 0.3 and 0.5 W m^{-2} K^{-1}, depending on the PCM used, which is lower than that of 0.8 W m^{-2} K^{-1} for a reference double-glazed unit. Goia, et al [5] applied a large integrating sphere (75cm diameter) to measure the spectral transmittance, reflection and absorption coefficients of a paraffin-based PCM window. For a window with 15mm thick PCM, the measured solar transmittance is 0.46 in the solid state and increases to 0.75 when fully melted in liquid state. Gowreesunker et al. [6] studied the thermal and optical characterisation of paraffin wax RT27 PCM glazing unit. It was found that during rapid phase changes, the transmittance spectra from the PCM are unstable. Visible transmittances of 40% and 90% were obtained at solid and liquid states, respectively. Grynning et al. [3] investigated the dynamic characterisation of a glazing system filled with PCM. The measured visible light transmittance and *U*-value of the window are approximately 0.08-0.24 and 0.5 W m^{-2} K^{-1}, respectively. PCMs have also been applied for the agricultural greenhouse, and their integration into non-transparent north walls is a widely adopted means for heat storage. Inorganic PCMs such as $CaCl_2 \cdot 6H_2O$ and $NaSO_4 \cdot 10H_2O$ are most frequently utilised as the energy storage medium for greenhouse heating purposes [7,8]. Boulard et al [9] packed 2970kg of an inorganic compound PCM ($CaCl_2 \cdot 6H_2O$) with a melting temperature of 22°C in PVC plastic containers, which were placed along the north wall in a 176m^2 greenhouse, in southern France. It was found out that this system can provide a heating energy saving of approximately 40%. Berroug et al [10] encapsulated 4cm thick $CaCl_2 \cdot 6H_2O$ with a melting temperature of 29°C into a north wall in a greenhouse in Marrakech, it was found out that due to the passive heating effect, the PCM wall would keep the air temperature approximately 4°C higher than the outdoor temperature during the night time. Guan et al. [11] studied on a Chinese-style solar greenhouse with a three-layer north wall, composed of an inner PCM layer, a load-bearing wall layer and an outer insulation layer. It was found that in January the heat loss through the PCM north wall was reduced by 4.5%–5.6% depending on the time. Moreover, the daily effective heat storage capacity of the wall system was enhanced by 6.6%–21.4%. Furthermore, the total plant production per square meter was improved by 71.4%.

This project develops a passive heat recovery and storage module, which is suitable for use in greenhouse skin (façade and roof). For this purpose, a thin layer of paraffin wax RT28 PCM with a melting temperature of 28°C was embedded into the ethene-co-tetrafluoroethene (ETFE) foil pane. This module, thus, aims to provide a suitable daytime light transmittance, to store unwanted heat and to maintain a more stable condition for the greenhouse. Heat stored during the day can be subsequently used during the night for the passive heating. At night, as the PCMs turn from transparent liquid into translucent solid, it will reduce heat loss from the greenhouse to the ambient environment. The developed system has been tested under various solar radiation intensities to monitor charging and discharging process. In addition, its performance has also been compared with the ETFE without PCM, and ETFE filled with water. Meanwhile, the optical performance of the developed module has been tested using a spectrometer and a pyranometer, respectively.

2. Experimental Investigation

Experimental studies of the developed heat recovery ETFE-PCM module were carried out at the laboratory in the Energy Technology Building, University of Nottingham. The experimental apparatus and the measurement procedures are described in this section.

2.1. ETFE

ETFE prototype module was manufactured consisting of four small pouches in which PCM material could be contained during the testing undertaken. The developed ETFE module has a dimension of 230mm x 230mm and the dimensions of the four internal pouches are all 100mm x 100mm. The ETFE module was manufactured with 200μm plain transparent ETFE films using heat welding techniques to create a water tight pocket and tests were carried out to ensure that there was no leakages prior to the testing with the PCM material. In addition, a ½" ETFE pipe was welded onto an opening on each ETFE pouch to allow for the PCM material to be poured via a funnel in the pouch. Once the ETFE pouch has been filled with the PCM, the pipe was then rolled up and clamped at the edge of the module to completely seal the ETFE pouch and preventing the PCM leaking during testing. Rubber gaskets were applied between the clamp and the ETFE module to minimize the heat transfer.

2.2. Selection of the Phase Change Materials

Most of the greenhouse requires an average and a maximum inner ambient temperature of 12-22°C, and 35-40°C, respectively [12]. The appropriate phase change material should therefore have a melt temperature around these numbers whilst higher than the summer average ambient air temperature in the UK to allow heat charge and discharge. Hence, RT28 solid to liquid phase change material which has a melting temperature of 26-28°C was chosen for this study. The characteristics of the PCM RT 28 are shown in Table 1. In the test, each ETFE pouch was filled with 60ml RT28.

Table 1: Thermophysical properties of the chosen phase change material RT28

Property	**RT 28(liquid)**
Main component	n-paraffin
Heat storage capacity ±7.5% (kJ kg^{-1})	160
Combination of latent and sensible heat in a temperature range of 19 ˚C to 34 ˚C (Wh/kg)	44
Melting temperature (˚C)	26-28
Density (kg m^{-3})	Solid 880 at 20˚C Liquid 750 at 30˚C
Specific heat capacity (kJ $kg^{-1}K^{-1}$)	1.8 Solid / 2.4 liquid
Heat conductivity (W m^{-1} K^{-1})	0.2
Flash point (˚C)	150
Volume expansion	12.5%

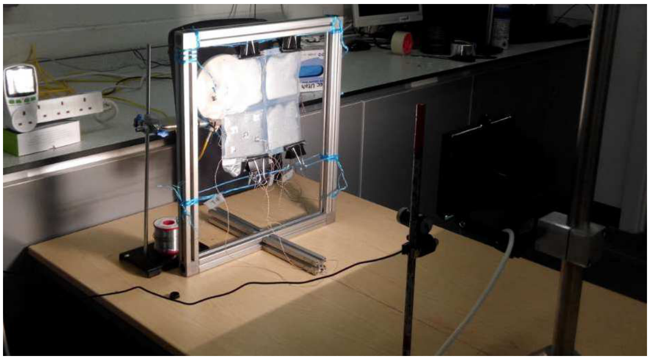
2.3. The apparatus setup

2.3.1 Optical measurement

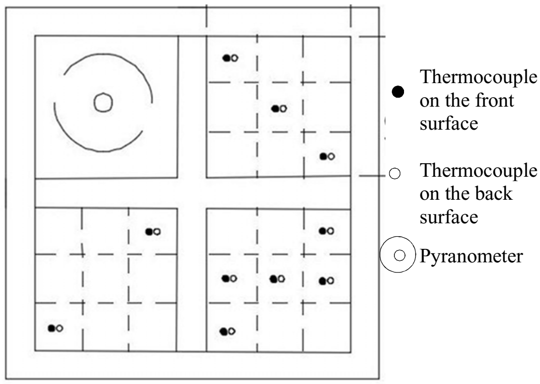
The transmittance of the developed ETFE-PCM module was undertaken by heating samples on a hotplate to a specific temperature allowing 20 minutes equilibration time before taking a measurement. Four T-type thermocouples were glued to the top and rear surface of the ETFE-PCM module and the temperature was taken as the average. Transmittance was measured using an Ocean Optics USB200+ spectrometer connected to a FOIS-1 integrating sphere (consisting of a 38.1mm diameter Spectralon sphere encased in an aluminium housing with a 9.5mm diameter input port that accepts light energy) using a HL-2000 Halogen Light Source.

2.3.2 Thermal performance characterisation

Extensive indoor experimental characterisation of the ETFE-PCM module, ETFE-water module and ETFE module alone were undertaken for the incident solar radiation intensities of 400W/m^2, 600W/m^2 and 800W/m^2 using a halogen lamp. Fig. 1 shows a schematic sketch of the test apparatus and positions of the thermocouples and pyranometer. Twenty T type thermocouples were attached on the front and rear surface of the module to measure surface temperatures. A pyranometer was placed behind the module to monitor the variation of the transmitted solar radiation intensities during the tests. The thermocouples and pyranometer were connected to a 24 channel data logger DT85 which logged data at 10 second intervals. Before the test, the thermocouples were calibrated. An air conditioning system set to 20˚C was used to control the ambient room temperature. A digital video camera was used to record the appearance change during the phase change process.



(a)



(b)

Fig. 1. (a) Experimental characterisation of the ETFE-PCM system using a halogen light; (b) detailed view illustrating the locations of the thermocouples and pyranometer on the surface of the system.

3. Results and discussion

3.1. Measured optical behavior of the ETFE-PCM module

The measured transmittances of the ETFE-PCM module during the phase change using spectrometer and pyranometer is shown in Figs 2 and 3, respectively. From Figs 2 and 3, it can be seen that fully melted RT28 has a higher transmittance than that in solid state. The reason is that the incident radiation on the ETFE-PCM module is scattered and absorbed when the PCM is at solid state. More specifically, the irregular paraffin crystals in the solid state exhibits optical anisotropy that results in the inconsistency of refractive indexes, which leads to strong scattering effect [5,6]. Therefore, it leads to highly diffuse transmittance. In addition, it can also be seen that before starting of the phase change process, the transmittance of the ETFE-PCM module decreases with the increase of temperature (from ambient temperature till 28°C). This might be associated to the fact that, the crystal lattice of the paraffin distorts and causes an increase of the reflectance of the PCM when the temperature increases, therefore, the transmittance reduces. Furthermore, the pyranometer showed a higher measured transmittance than that measured by a spectrometer, this might be a result of a large dome in the pyanometer that receives the incident direct and diffuse solar radiation while the receiver of the spectrometer is relatively small, and mainly used to only measure the direct incident of the irradiance.

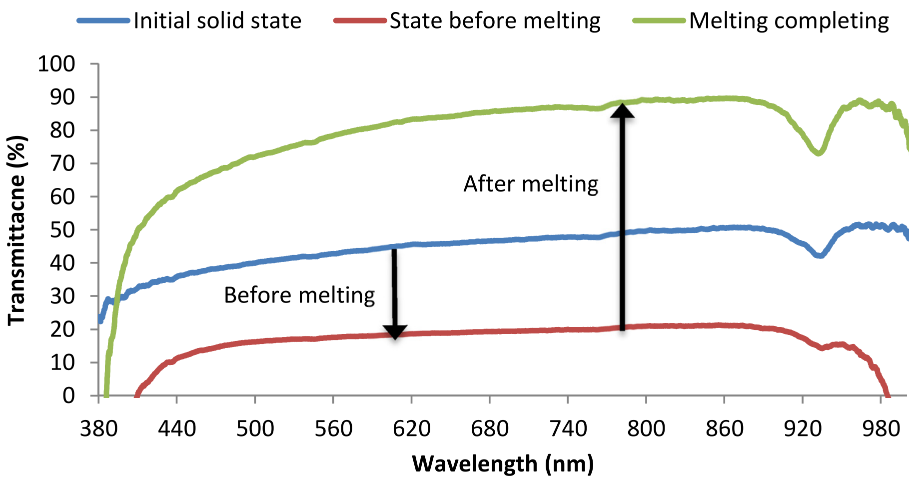


Fig. 2. Spectrum transmittance of the ETFE-PCM module from starting point till phase change completing

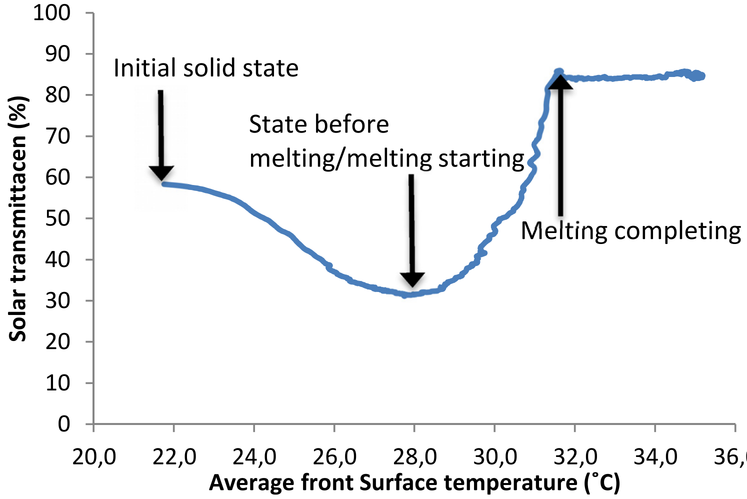


Fig 3 Transmittance of the ETFE-PCM module measured by the pyranometer

3.2. Measured thermal behavior of the ETFE-PCM module

The thermal characterisation of the ETFE-PCM module over a heat charging and discharging cycle under different incident solar radiation intensity is illustrated in Fig. 4. The measured variation of average front surface temperatures for the ETFE-PCM, ETFE-Water and ETFE alone at a solar radiation intensity of 600W/m^2 are shown in Fig. 5. From Fig 4, it can be seen that it takes approximately 1, 1.5 and 2.5 hours for the PCM to complete the charging process at average incident solar radiation intensities of 400, 600 and 800W/m^2, respectively. The front surface achieves a maximum temperature of approximately 41˚C for an incident solar intensity of 800W/m^2, and approximately 32˚C at incident solar radiation intensity of 400W/m^2. During the discharging process, after the temp-

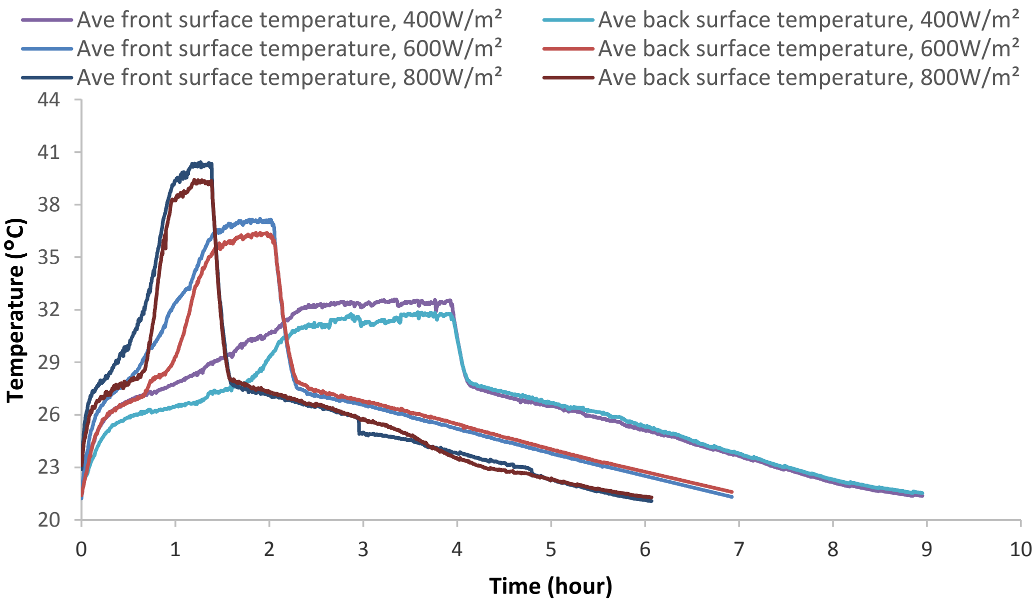


Fig. 4. Measured ETFE-PCM module temperature with time with the average incident solar radiation of 400, 600 and 800W/m^2.

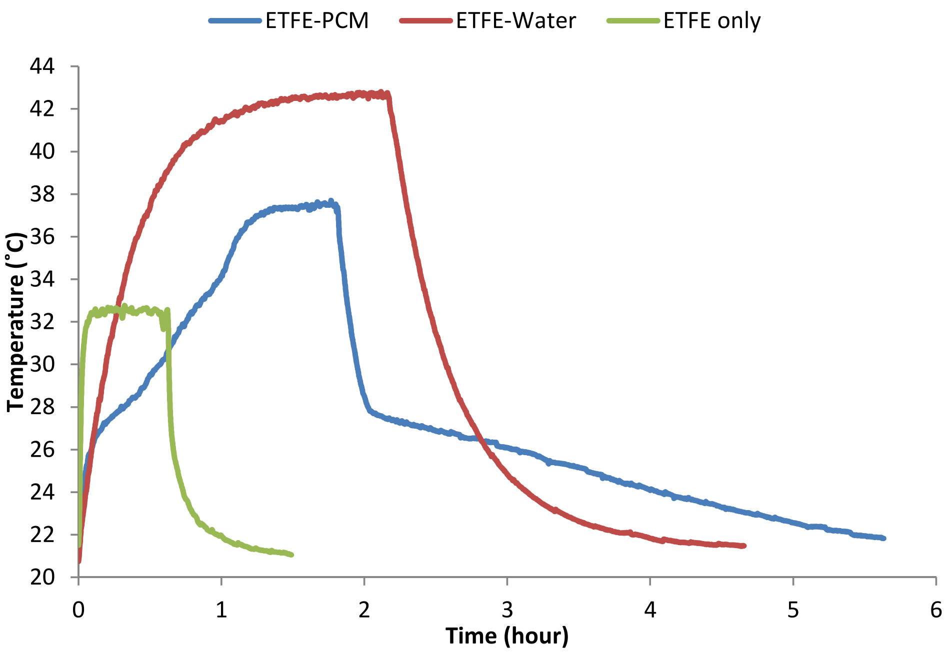


Fig.5. Measured ETFE-PCM, ETFE-Water and ETFE modules temperature with time with the average incident solar radiation of 600 W/m^2.

-erature decreases to the phase change temperature of 28˚C, the time for temperature decreases from 28 ˚C to ambient temperature is similar for the three tests. From Fig 5, it can be found that at incident solar radiation intensity of 600W/m^2, ETFE alone achieves a maximum temperature of 32˚C within a few minutes. ETFE-Water system takes approximately an hour to achieve a maximum temperature of approximately 42˚C. ETFE-PCM module reaches maximum temperature of approximately 37˚C after 1.5 hour. The ETFE-water and ETFE-PCM has a higher temperature than the ETFE alone, this is because they have a lower transmittance and higher absorptance than that of the ETFE alone. Although ETFE-PCM has lower temperature than that of the ETFE-Water, due to higher transmittance, however, the duration of the heat discharging of the ETFE-Water system is around 2 hours, which is approxmately half of that of the ETFE-PCM system.

4. Conclusion

In this paper, a novel envelope system composed of a double-layer ETFE and a RT28 phase change material is proposed as a potential strategy to better manage the interior temperature of a greenhouse. The selected RT28 paraffin wax has a melting temperature range of 26–28 °C and a latent heat of fusion of 160 kJ/kg. The optical measurement shows that the transmittance of the developed ETFE-PCM module is lower before phase transition, when compared with after phase transition state. In addition, the optical transmittance decreases with the temperature increase from the initial solid state to 28°C. In terms of thermal characterisation, the solar radiation intensity has a large effect on the heat charging period as well as peak surface temperature. This indicates that the thermal performance of ETFE-PCM integrated greenhouse would be sensitive to the conditions of solar irradiation and thus caution should be taken for the optimum design for different climatic regions. In the tests of ETFE alone, the ETFE-PCM and ETFE-Water system, it was found that the proposed system exhibits longer heat discharging period, which would be a benefit for the plant freezing protection inside the greenhouses in the UK where the winter has a long night time.

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